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A REVIEW OF SHOCK MITIGATION TECHNIQUES

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14. ABSTRACT
Shock mitigation methods (i.e., techniques for attenuating high amplitude stresses with high frequency content) are of great importance in defense applications. This presentation focuses on classifying and critically evaluating these techniques using categories based on the physical mechanism responsible for the mitigation. For example, crushable structures such as automotive "crumple zones" effectively attenuate single shock loads via irreversible deformation (plasticity), but they can also amplify subsequent shock loads. Other mitigation mechanisms include phase transformations, viscous dissipation, wave mode conversion, and stress wave redirection. A "bottom-up" approach is used to define shock mitigation performance, beginning with simple 1-D models of stress wave transport through a multiple component system. Transmission and reflection performance of the mitigating material(s) are defined, calculated, and verified using simple experiments. Finally, approaches for improving the overall mitigation performance using topological optimization will be discussed.

15. SUBJECT TERMS
Hard target fuzes, intelligent fuzes, hard target penetration, shock, instrumentation, shock sensors, recorders, accelerometers, pressure sensors, strain gages

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A Review of Shock Mitigation Techniques

85th Shock & Vibration Symposium

Reston, VA

27 October 2014

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Outline

- **Introduction**
  - Motivation of Shock Mitigation Technology

- **Review of Shock Mitigation Techniques**
  - Current approaches

- **Shock Mitigating Metamaterials**
  - Characteristics of Mechanical Metamaterials
  - Computational framework
  - Optimization

- **Summary**

Introduction

- *Impact and shock is relevant to many fields*
  - Crash testing   Blast protection
  - Defense   Oil & Mining
- Common features
  - Impulse stress waves
    - Short rise time
    - High frequency
    - High amplitude
  - Wide range of damage
    - Sensor resonance
    - Material failure
    - Fatigue, etc.

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N   100 METERS
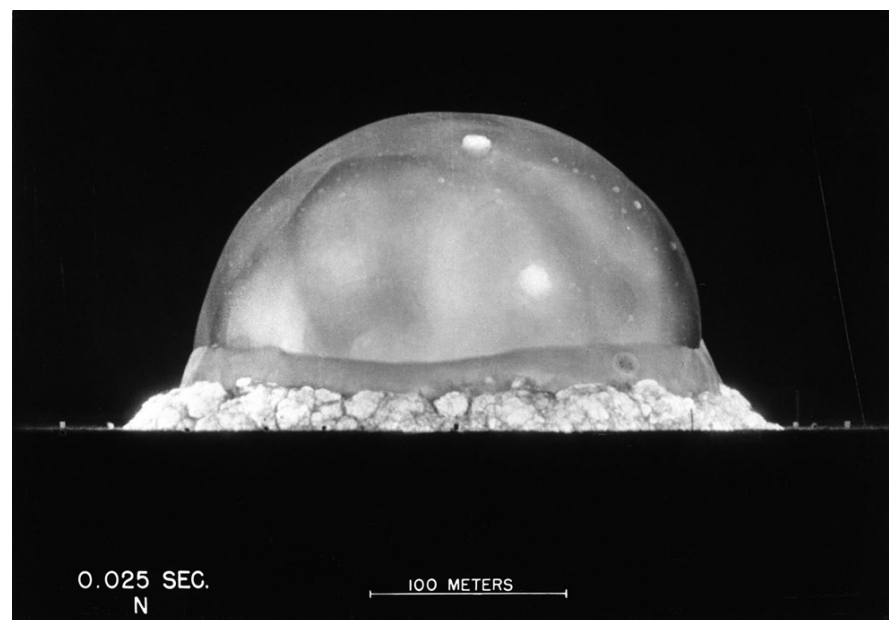
Motivation and Approach

Motivation:
- Improve the survivability of fuzes and electronic subsystems in high shock environments

Approach:
- Design, Develop, and Demonstrate shock mitigation technology

Mechanical Deformation
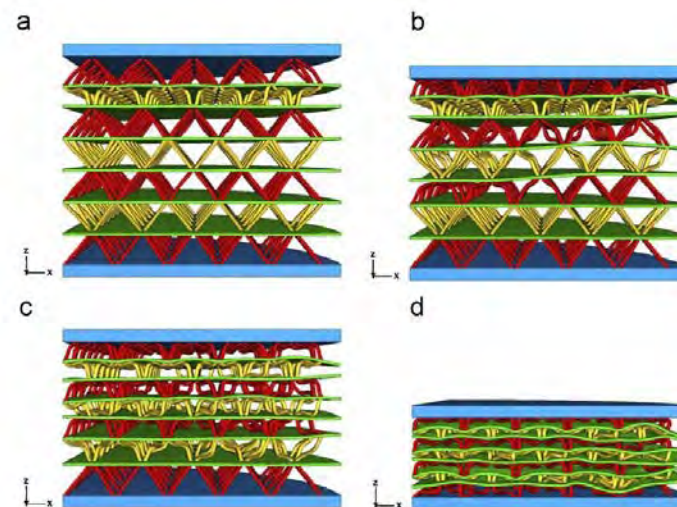
- Crumple Zones
  - e.g., Crushable Cellular Material [1]
 - Low and Intermediate Velocity Impact
  - Mainly Inelastic → One Shot

[1] H. Wadley, K. Dharmasena, Y. Chen, P. Dudt, D. Knight, R. Charette, and K. Kiddy, "Compressive response of multilayered pyramidal lattices during underwater shock loading", International Journal of Impact Engineering 35 (2008) 1102–1114

Viscoelastic
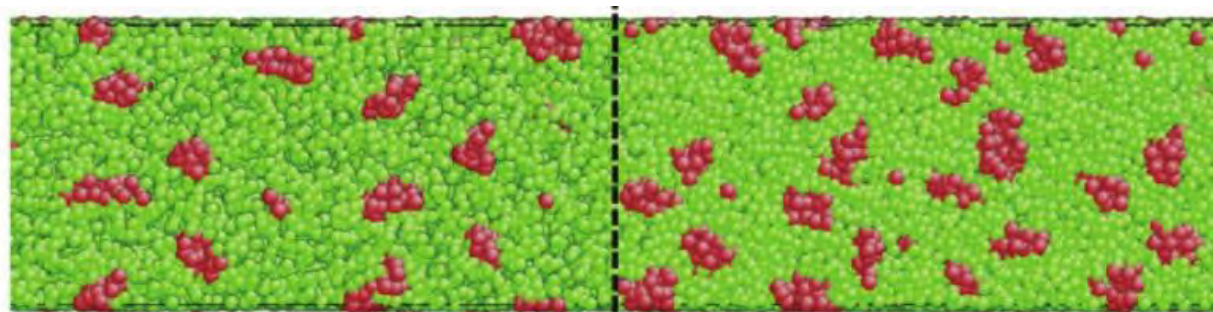
- Polyurea
  - energy dissipation from hard and soft domains [2]
- Polysulfide
 - mechanical isolator [3]

Sensor
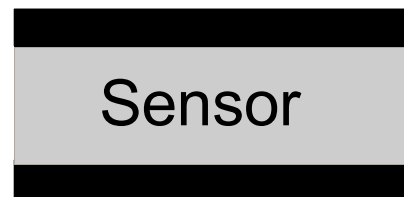
[2] Bedri Arman, A. Srinivas Reddy, and Gaurav Arya, "Viscoelastic Properties and Shock Response of Coarse-Grained Models of Multiblock versus Diblock Copolymers: Insights into Dissipative Properties of Polyurea", Macromolecules, 2012, 45 (7), pp 3247–3255

[3] Bateman, V. I., Brown, F. A., and Nusser, M. A., 2000, "High Shock, High Frequency Characteristics of a Mechanical Isolator for a Piezoresistive Accelerometer, the ENDEVCO 7270AM6," Report SAND2000-1528 Sandia National Laboratory

Superelastic
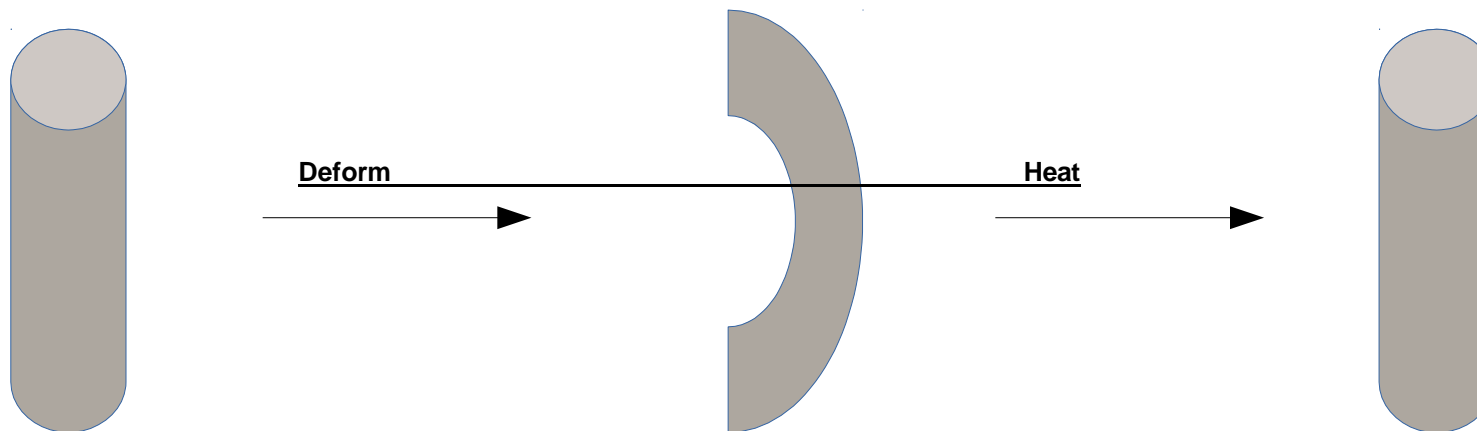
- NiTi→ Shape Memory Alloy (SMA)
- Strength of metal and flexibility of plastic
- Dissipated energy from phase transformations
- Kink and crush Resistant
- Large amount of recoverable deformation

[4] S. Nemat-Nasser and W.-G. Guo, 2006, "Superelastic and cyclic response of NiTi SMA at various strain rates and temperatures", *Mech Materials* 38, pp 463-474.

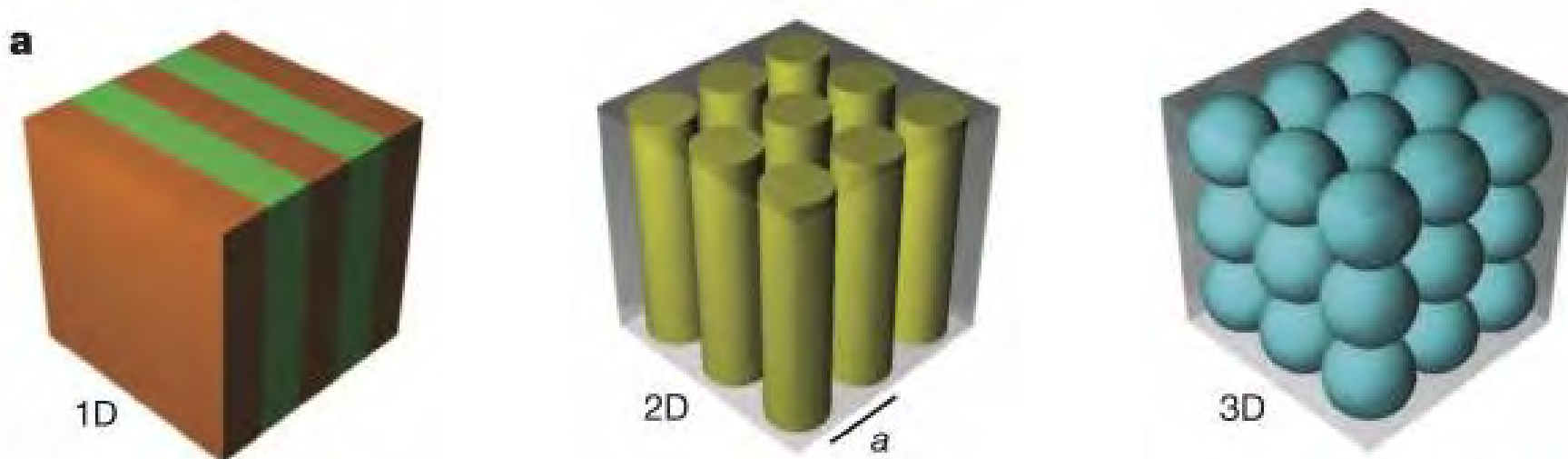# Constrained Layer Damping

$t = 0$ msec
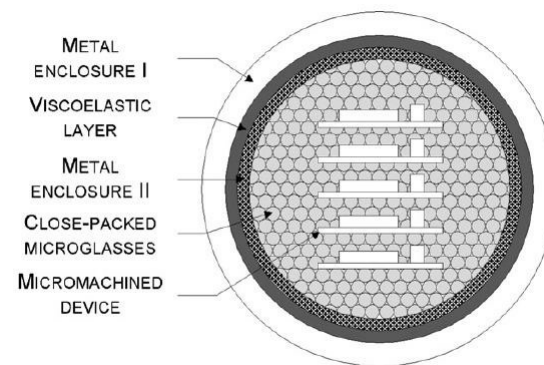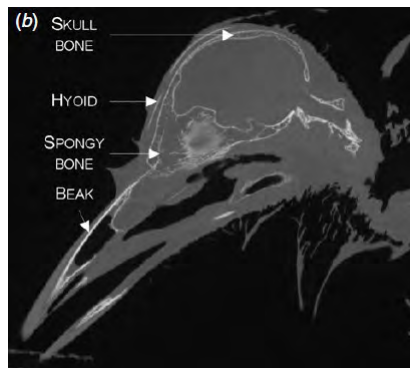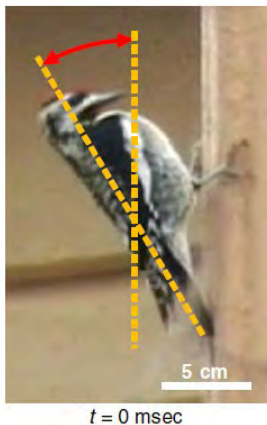
- Biomimetic – Biologically inspired

- Mimics constrained layer damping mechanism found in the woodpecker skull

[6] Yoon, S.-H., and Park, S., 2011, "A mechanical analysis of woodpecker drumming and its application to shock-absorbing systems," Bioinspiration & Biomimetics, 6(1), p. 016003.

Mechanical Metamaterials


1D   2D   3D

- Allows one to tailor the physical properties of composite systems at the continuum scale, even to the point in which unphysical properties emerge

- Mechanical properties are determined by the shape, interfaces, and sizes of the composing materials

[6] M. Maldovan, "Sound and Heat Revolutions in Phononics," *Nature*, 503, p. 209-217 (2013).

1-D Mechanical MetaFilter

Incoming wave — MetaFilter — Outgoing wave
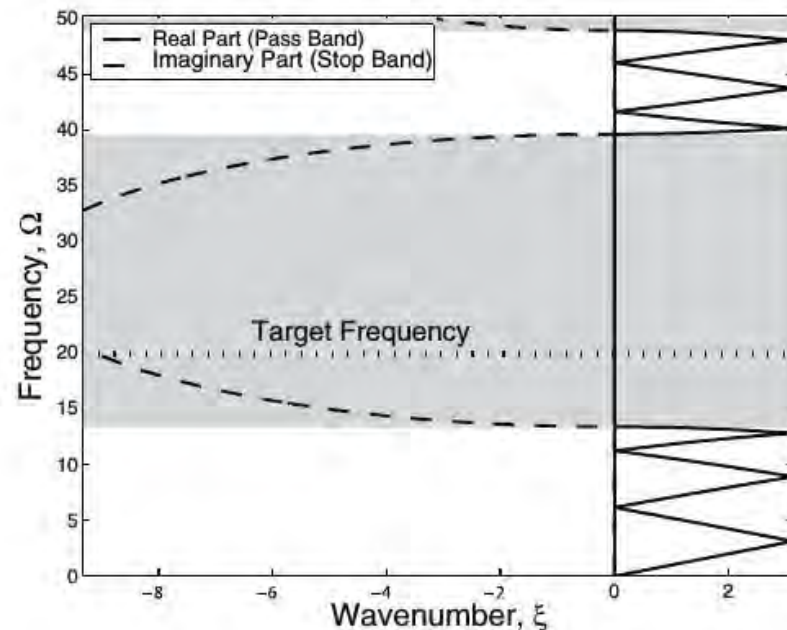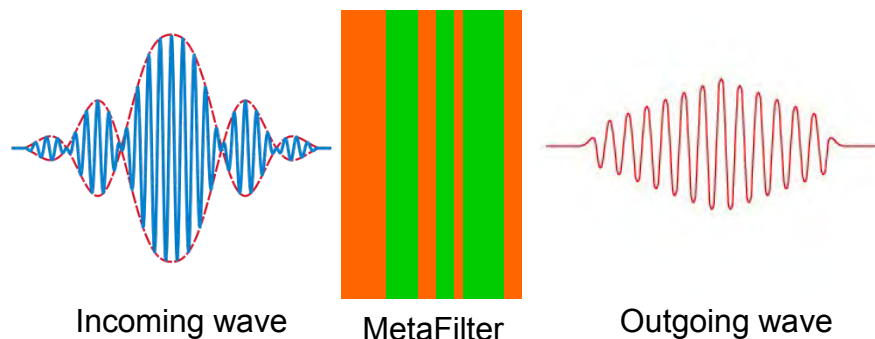
- Given a material, determine layer size which filters mechanical waves in a desired frequency range
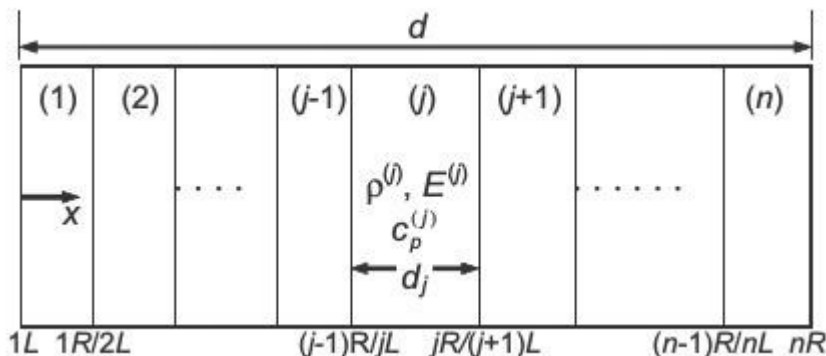
[7] N.A. Winfree et al, 2010, "Mechanical filter for sensors", US Patent 7706213

[8] Hussein, M.I., Hamza, K., Hulbert, G.M., Scott, R. A., and K. Saitou, "Multiobjective evolutionary optimization of periodic layered materials for desired wave dispersion characteristics," *Structural and Multidisciplinary Optimization*, 31, p. 60-75 (2006).

Theoretical Framework

Unit Cell

$$\rho(\boldsymbol{r}) \frac{\partial^2 \boldsymbol{u}(\boldsymbol{r})}{\partial t^2} = \nabla \cdot \boldsymbol{\sigma}(\boldsymbol{r})$$

$$\mathbf{T}_j = \begin{bmatrix} \cos(k^{(j)}d^{(j)}) & (1/Z^{(j)})\sin(k^{(j)}d^{(j)}) \\ -Z^{(j)}\sin(k^{(j)}d^{(j)}) & \cos(k^{(j)}d^{(j)}) \end{bmatrix}$$

- Transfer matrix method
  - Assume infinitely periodic layered material consisting of a repeated unit cell
  - Solve elastodynamic equation for the unit cell consisting of *n* layers
  - Use periodicity of the material to compute band structure

[9] Mahmoud I. Hussein, Gregory M. Hulbert, and Richard A. Scott, "Dispersive elastodynamics of 1D banded materials and structures: analysis", Journal of Sound and Vibration 289 (2006) 779–806
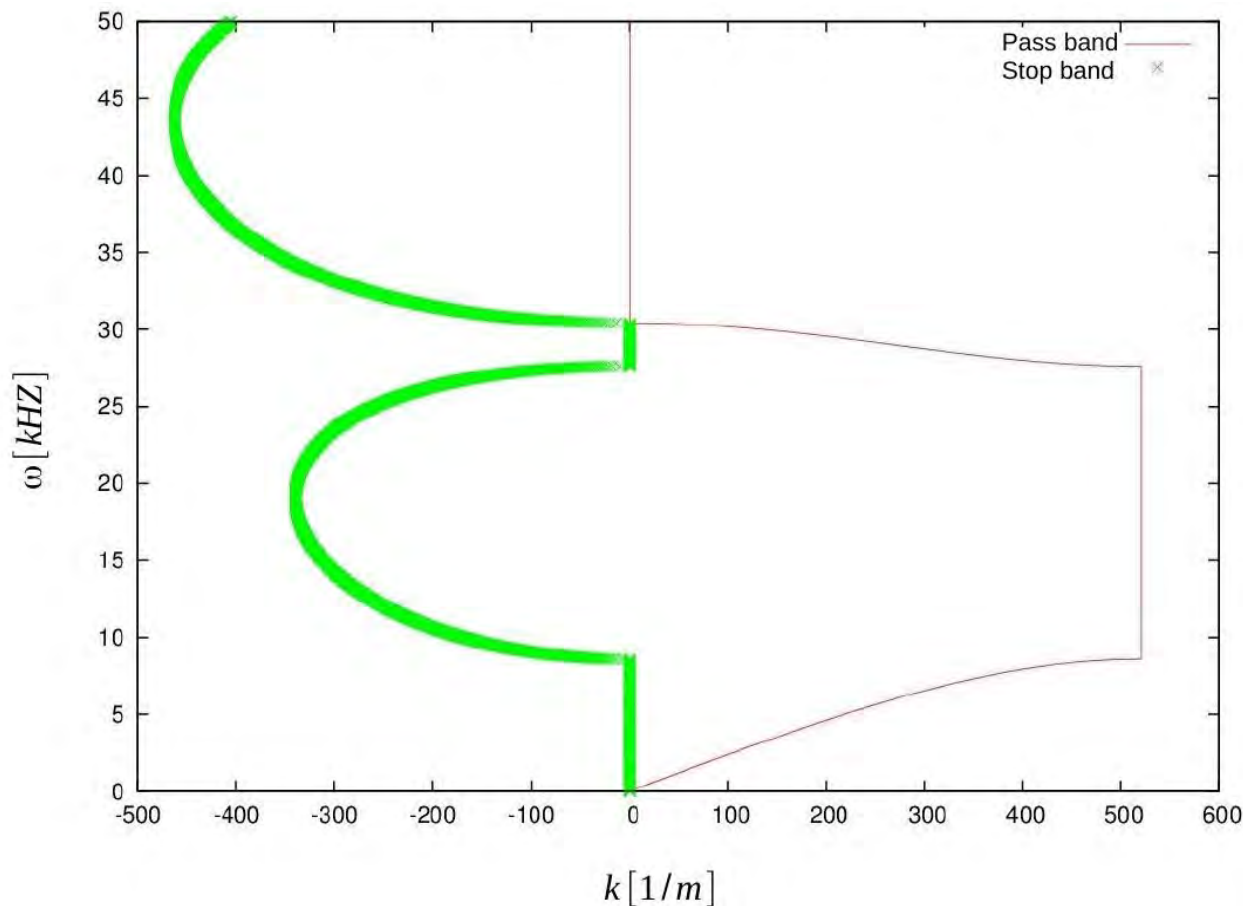
Computational Design
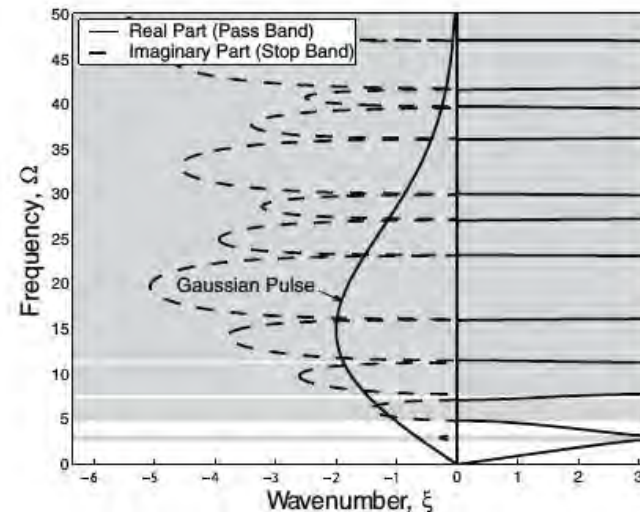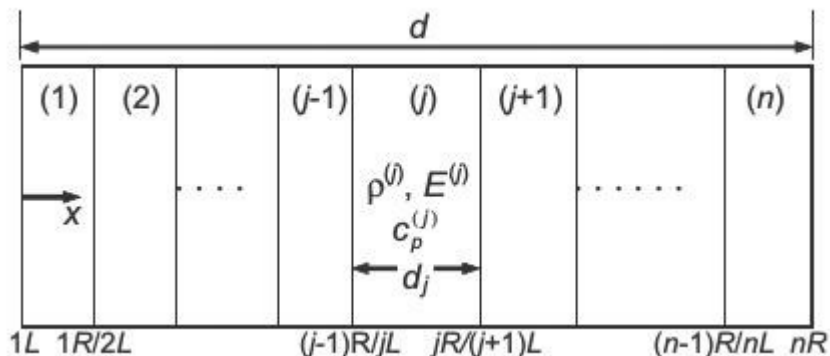
- Couple continuum level simulation with optimization algorithms to obtain the optimum design parameters.
- Shock Filter Design: fitness function involves a weighted penalty for a passband in a specified frequency range.
- Design parameters: layer thickness, number of layers, density, elastic modulus.

[10] Hussein, M.I., Hamza, K., Hulbert, G.M., Scott, R. A., and K. Saitou, "Multiobjective evolutionary optimization of periodic layered materials for desired wave dispersion characteristics," *Structural and Multidisciplinary Optimization*, 31, p. 60-75 (2006).
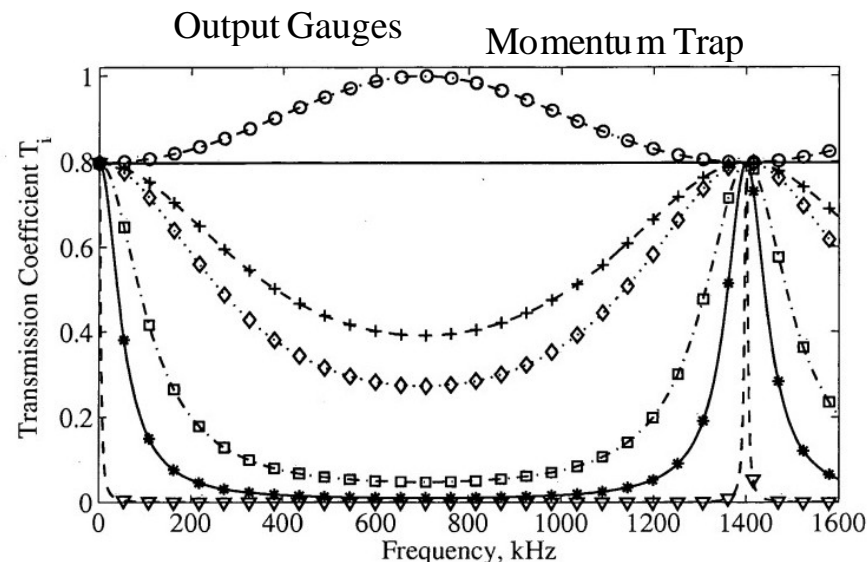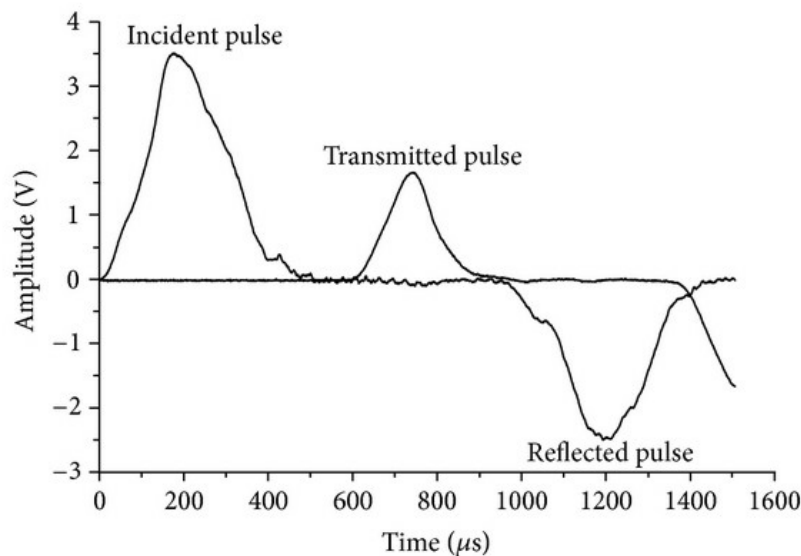
Potential MetaFilter

HDPE and Aluminum
MetaFilter

- 10 layer unit cell of Polyethylene (HDPE) and Aluminum layers on the order of mm-μm

Striker Bar

Input Bar   Sample   *Output Bar*

Gas Gun

Input Gauges

Output Gauges

Momentum Trap
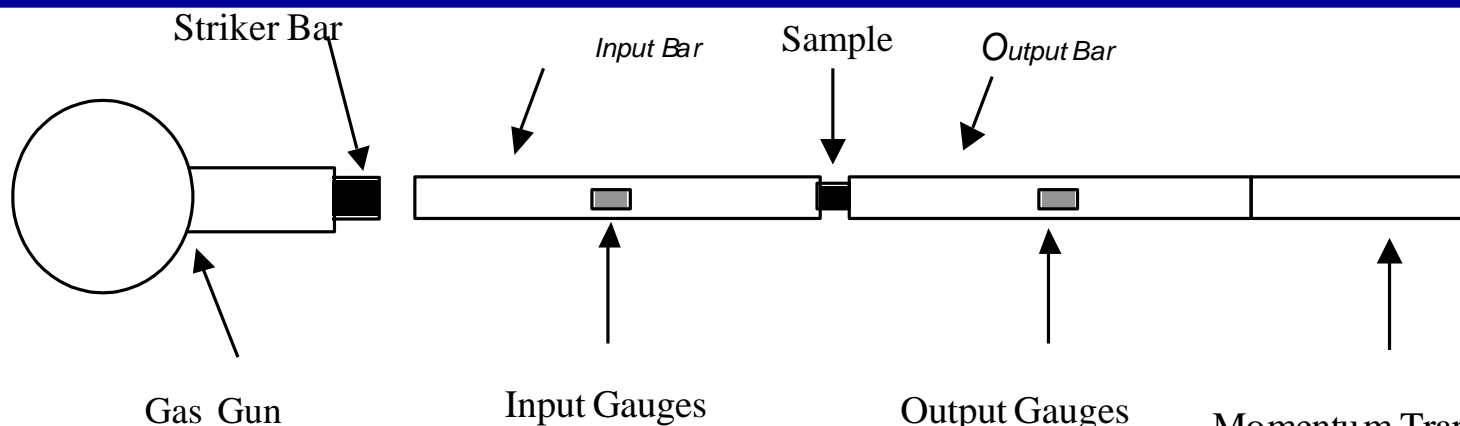
[10] N.A. Winfree et al, 2010, "Mechanical filter for sensors", US Patent 7706213

[11] Jordan, J.L., C.R. Siviour, J.R. Foley, and E.N. Brown, "Compressive Properties of extruded polytetrafluoroethylene," *Polymer*, 48 [14], p. 4184-4195 (2007).

Summary

- ## Shock mitigation is a difficult task
  - High Frequency, High Amplitude Stress Waves
  - Wide range of shock induced systems failure

- ## Many current technologies and techniques exist
  - Mechanical Deformation
  - Viscoelastic
  - Superelastic
  - Constrained Layer Damping
  - Biomimetic
  - …

- ## Mechanical metamaterials provides a robust framework to develop shock mitigating technology
  - Properties are determined by the shape, interfaces, and sizes of the composing materials
  - Computational design for specific application

Acknowledgements

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